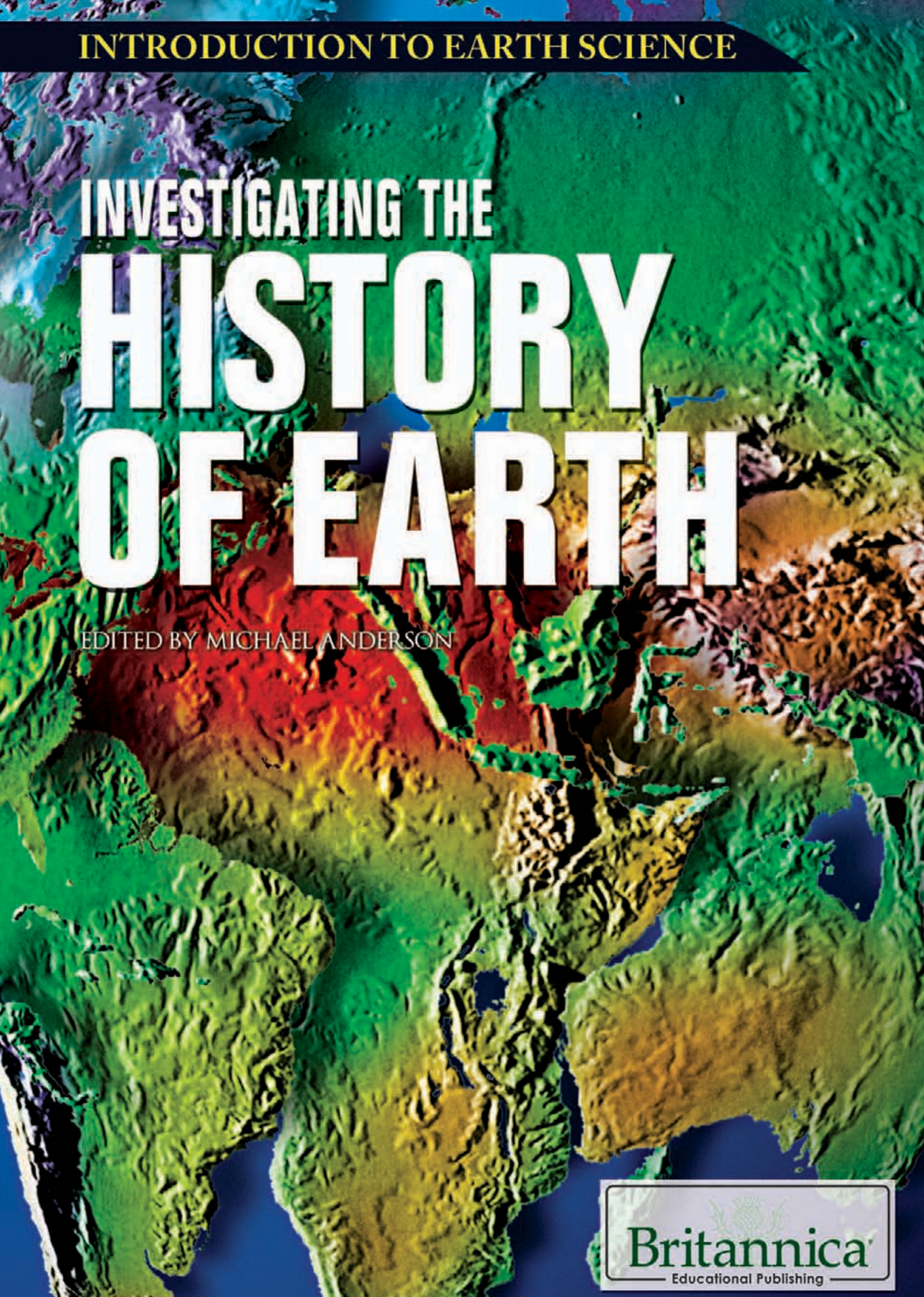
INTRODUCTION TO EARTH SCIENCE



INVESTIGATING THE HISTORY OF EARTH

EDITED BY MICHAEL ANDERSON

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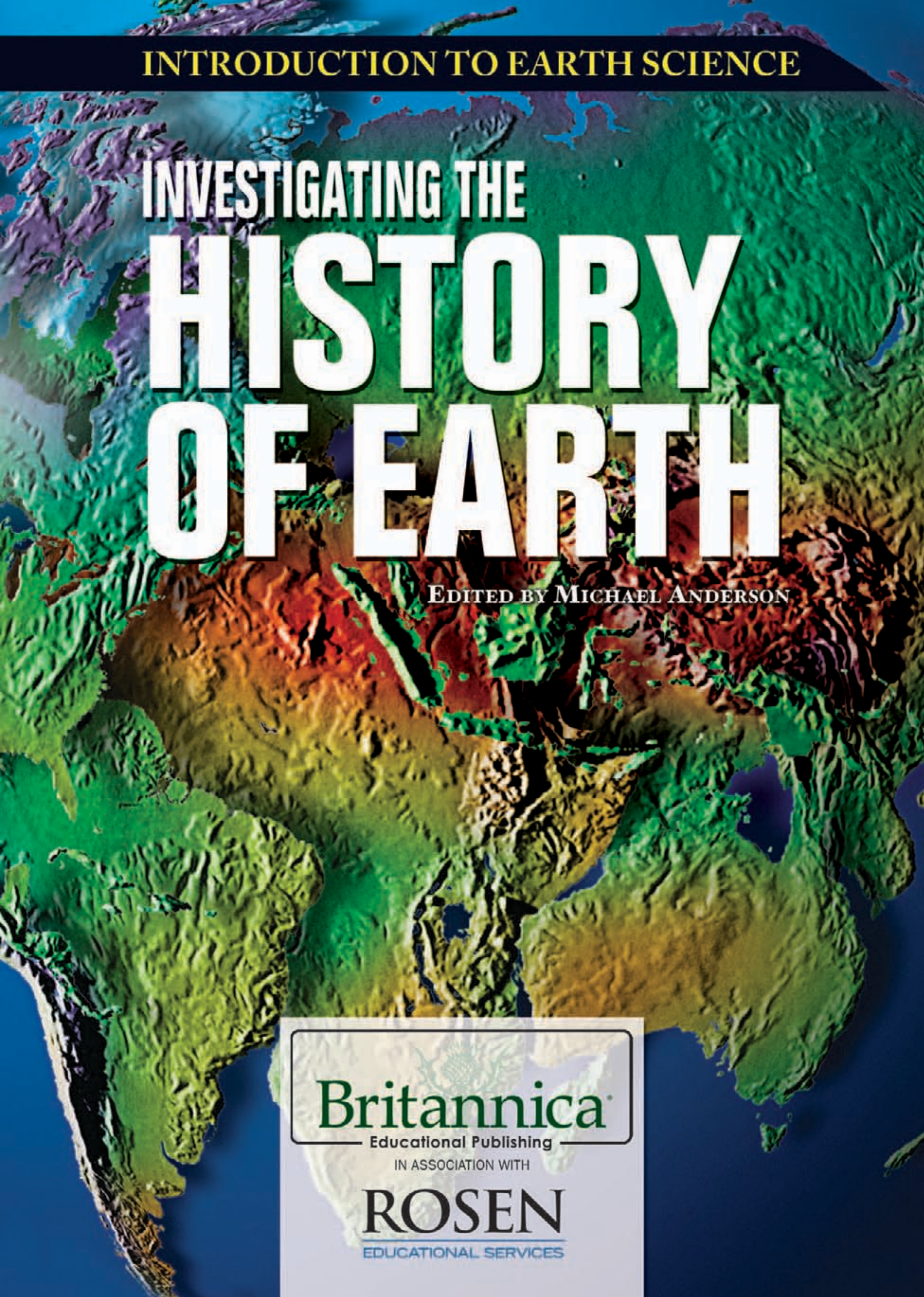

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On the cover, page 3: Throughout the history of Earth, the continents have periodically broken up and reassembled as supercontinents. *Russ Widstrand/Workbook Stock/Getty Images*

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INTRODUCTION

Every day we walk across its surface, admiring its variety of plants, animals, and landscapes. Earth has taken billions of years to evolve into the planet we now inhabit. This volume examines this long history, from Earth's origins in a cloud of gas and dust to its place as a planet teeming with life. It addresses questions that scientists have long debated: how, why, and when did Earth form and develop into this complex and intriguing planet?

Scientists believe that Earth, as well as the rest of the solar system, began to form about 4.6 billion years ago from a gas and dust cloud called a nebula. Under the force of gravity, the nebula's particles came together to form objects that grew larger and larger, eventually forming the planets. At first Earth's surface was unstable, covered with seas of molten rock. As the surface cooled, the crust—Earth's solid outer layer—began to form. No one knows when the first crust formed: though scientists have generally dated the oldest rocks to about 4 billion years ago, discoveries of some older minerals have led some to believe that stable crust existed hundreds of millions of years earlier.

To help study Earth's history, scientists have devised a scale of geologic time. The scale provides a framework for studying the evolution of the continents, oceans, atmosphere, and biosphere—the

Earth's origins have occupied the minds of many scientists through the ages. **NASA**

"zone of life" that consists of all living things. Earth's surface consists of layers of rock formed from pebbles, sand, and mud deposited by water, wind, or glaciers. The oldest layers are lower down, and the more recent layers are on top. In studying these rocks, scientists found that each layer contained distinctive fossils and that the layers were similar all over the world. They then classified and dated each layer of rock and their fossils to create the geologic time scale.

Geologic time is divided into eons, each of which is divided into smaller units of time. The oldest eon is the Archean, which lasted from about 4 billion years ago to 2.5 billion years ago. During this period the first living things appeared. Because the atmosphere contained little oxygen, however, life was limited to microorganisms that could survive without it. Oxygen levels increased significantly during the Proterozoic eon, which lasted from about 2.5 billion years ago to 542 million years ago. Bacteria, fungi, simple plants, and complex organisms, including the first animals, evolved.

The Phanerozoic eon, stretching from about 542 million years ago to the present, saw a rapid expansion and evolution of life. It is divided into three major time

periods largely on the basis of characteristic life-forms: the Paleozoic, Mesozoic, and Cenozoic eras. The Paleozoic began 542 million years ago with the Cambrian explosion, an extraordinary diversification of marine animals, and ended 251 million years ago with the extinction of most marine and land species. The Mesozoic era began 251 million years ago and ended about 66 million years ago. The ancestors of major plant and animal groups that exist today first appeared during the Mesozoic, but this era is best known as the time of the dinosaurs. The Cenozoic era, the Age of Mammals, began at the end of the Mesozoic and continues to the present.

During the Phanerozoic eon, Earth gradually assumed its present configuration and physical features through such processes as plate tectonics, mountain building, and continental glaciation. Thus, though the Phanerozoic represents only about the last one-eighth of time since Earth's crust formed, its importance far exceeds its relatively short span of time.

With such strong evidence of a constant fluctuation of life, land, and climate, we are apt to be in the midst of more change. We may not know exactly what changes will occur next, but we can learn from the history of our lively and varied planet.

CHAPTER 1
EARTH'S ORIGINS

The origin of Earth has been a subject of great interest among scientists for a long time. By the late 1800s geologists and biologists had collected evidence suggesting that Earth is at least hundreds of millions of years old, much older than they had thought. Geologists reasoned that vast stretches of time were needed for the slow work of erosion and sedimentation to have had the effects they apparently had. Biologists felt that a long time was also needed for evolution to have resulted in the great diversity of life seen today.

There were dissenting opinions, though. Physicists such as Lord Kelvin calculated that Earth, apparently still molten inside, should have cooled to a solid throughout if it were more than about 40 million years old. Similarly, astronomers figured that the Sun could not be more than a few tens of millions of years old. They believed that the Sun shone because of energy from gravitational contraction, so it could not have sustained its energy output for so long without a drastic reduction in size.

The discovery of radioactivity by Henri Becquerel in 1896 led to a solution to both problems. Earth could be heated internally by radioactive decay of elements such as uranium deep inside, and this could last billions of years. The Sun, it turned out, shines by nuclear fusion, giving it a potential lifetime of at least 10 billion years.

Radioactive dating of rocks played a crucial role in calculating Earth's age. Some isotopes (forms of an element with different atomic masses) of some elements, such as uranium, decay by emitting radiation in the form of smaller particles, such as electrons and alpha particles. This leaves behind a succession of "daughter" products, such as lead. The rates of decay have been measured with great precision in laboratories. By measuring the ratios of the daughter products to the original radioactive elements, and assuming that the materials were trapped in a rock from the time it solidified, the age of the rock can be calculated.

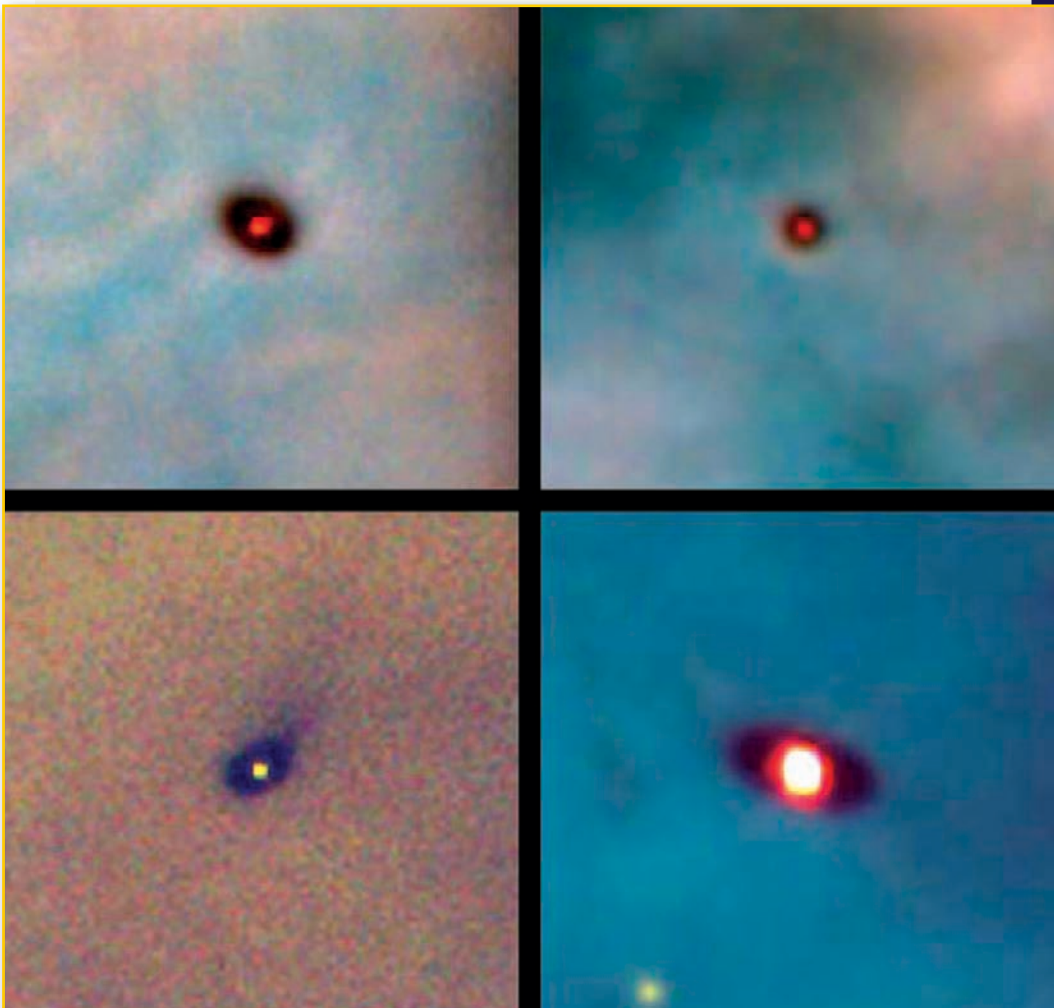
Rocks from the seafloor are rarely found to be older than 200 million years, but those from the continents are occasionally found to date back more than 3 billion years. In 2001 Australian researchers announced the discovery of a small grain of zircon (a mineral

containing zirconium) that they dated to 4.4 billion years ago. Moreover, meteorites, which likely formed at about the same time as Earth, have been dated to about 4.5 billion years ago. These findings help pin down a likely age of about 4.55 billion years for Earth itself.

The Formation of Earth

It is believed that Earth formed, along with the rest of the solar system, from a cloud of gas and dust called a nebula. Nebulae are seen today in other parts of the Milky Way and also in other galaxies. Astronomers have found evidence of stars and planetary systems forming in many of these nebulae, as the mutual gravitational attraction of the nebula's particles pulls them together.

According to this theory, called the nebular hypothesis, the cloud consisted mainly of hydrogen and helium, most of which ended up in the Sun. The outer planets—Jupiter, Saturn, Uranus, and Neptune—are quite different from Earth. They were far enough from the Sun and therefore cold enough that these gases (along with other compounds such as methane, ammonia, and water) were able to gravitationally collect around small rocky or metallic cores.



Disks of gas and dust around young stars in the Orion nebula about 1,500 light-years away may be new solar systems in the making. Four images taken by the Hubble Space Telescope show disks surrounding four different stars that are only about a million years old. The planets of our solar system are thought to have arisen from such a protoplanetary disk about 4.6 billion years ago. The central glow in each image is the star. The disks range in size from about two to eight times the diameter of our solar system. NASA

The inner planets—Mercury, Venus, Earth, and Mars—were warmer and also exposed to a stronger solar wind. These effects drove most of the light gases out into space, leaving these planets as solid bodies. Venus and Earth, and to a lesser extent Mars, retained atmospheres, but only as fairly thin envelopes surrounding the rock and metal.

The planets formed by accretion—a collecting together of smaller objects—mainly because of gravity. The late stages of accretion took the form of impacts of meteoroids and comets. Some impacts must have been tremendously energetic, likely melting much or all of Earth's early crust. The most widely accepted theory of the Moon's formation suggests that a "protoplanet" at least half of Earth's diameter struck, blasting material from both it and Earth into space. Some of this material then collected together to form the Moon. This event probably happened sometime during Earth's first 100 million years.

FIRST BILLION YEARS

The earliest period of Earth's history has been called the Hadean, after Hades, the underworld abode of the dead in ancient

Formation of the Solar System

Astronomers believe that the solar system formed as a by-product of the formation of the Sun itself some 4.6 billion years ago. According to the prevailing theory, the Sun and its many satellites condensed out of the solar nebula, a huge interstellar cloud of gas and dust. The solar system began forming when the gravity of this interstellar cloud caused the cloud to start contracting and slowly spinning. This could have been caused by random fluctuations in the density of the cloud or by an external disturbance, such as the shock wave from an exploding star.

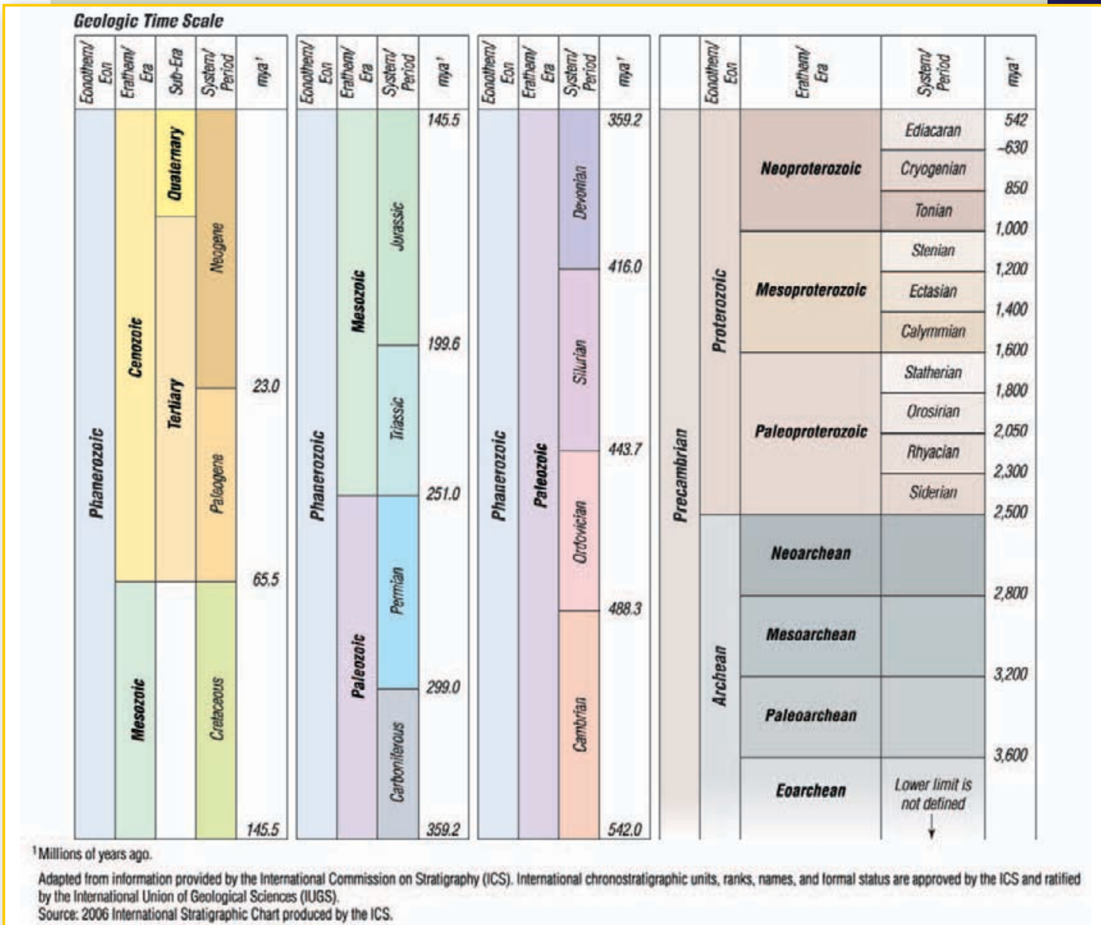
As the interstellar cloud squeezed inward, more and more matter became packed into the center, which became the protosun (the material that later developed into the Sun). The contraction caused the cloud to spin faster and faster and to flatten into a disk. Eventually, the center of the cloud collapsed so much that it became dense enough and hot enough for nuclear reactions to begin. The Sun was born.

Meanwhile, away from the center, the gas and dust in the spinning disk cooled. Solid grains of silicates and other minerals, the basis of rocks, condensed out of the gaseous material in the disk. Farther from the center, where temperatures were lower, ices of water, methane, ammonia, and other gases began to form.

The spinning material in the disk collided and began to stick together, forming larger and larger objects. Ultimately, some of the clumped-together objects grew huge and developed into planets. The inner planets formed mostly from chunks of silicate rock and metal, while the outer planets developed mainly from ices. Smaller chunks of matter and debris that were not incorporated into the planets became asteroids (in the inner part of the solar nebula) and comet nuclei (in the outer part of the nebula). At some point after matter in the nebula had condensed and clumped into objects, the intensity of the solar wind seems to have suddenly increased. This blew much of the rest of gas and dust off into space.

Greek religion. It has been believed that the leftover heat of formation, combined with frequent impacts, would have rendered Earth a hellish place, with red-hot seas of glowing magma. However, the existence of the 4.4-billion-year-old zircon crystal suggests the surface may have cooled more quickly than previously thought. The ratio of certain oxygen isotopes in the zircon also suggests it formed in the presence of water. This means temperatures must have been below the boiling point—and some water present—in at least some areas by the time the crystal formed.

Much of Earth's first billion years is shrouded in mystery, partly because so few rocks remain from that time. Most of them have been through repeated cycles of being



A time scale indicates the names and time ranges of different eons, eras, periods, and other divisions of geologic time, from the Archean eon more than 3.6 billion years ago, at bottom right, to the present Neogene period, at upper left. **Encyclopædia Britannica, Inc. Source: International Commission on Stratigraphy (ICS)**

subducted and melted, with the material eventually surfacing in the middle of oceans. The Moon bears witness to quite a violent period in its own history, and surely Earth's as well. Results from the Apollo Moon exploration program show that most lunar craters (which are the results of impacts) formed prior to 3.8 billion years ago, with many of them from just before that time. Scientists believe that around 3.9 billion years ago impacts by comets and meteoroids were quite frequent. This event, called the late heavy bombardment, may have resulted from migrations of Uranus and Neptune disturbing the orbits of smaller bodies in the outer solar system and sending them sunward, so that they would then strike the inner planets.

After this period, certain pieces of crust survived. A good example is the Canadian Shield, which constitutes much of that country. Several places there have rocks about 3.8 billion years old (with some dating back about 4 billion years). Oceans probably existed, but instead of large continents, it appears there were smaller bodies of land, such as arcs of volcanic islands. Eventually, many of them drifted together and combined to form the first continents.

Precambrian bedrock of the Canadian Shield rises out of Reindeer Lake, on the border between northeastern Saskatchewan and northwestern Manitoba. © Richard Alexander Cooke III

Astronomers studying and modeling the life cycles of stars believe that at that time the Sun was only about 75 percent as bright as it is now. This should have made Earth quite cold, at least when large impacts were not occurring. Without something to trap the Sun's heat, the oceans might have completely frozen over, with the early continents covered in snow. Calculations show that the

white surface would have reflected away so much of the Sun's light that the planet would still be in a deep freeze today.

In fact, it appears there was something to keep the planet warm: Earth's early atmosphere. The gases carbon dioxide and methane are believed to have been much more abundant at that time than they are now. They were probably released mainly through volcanic activity. Both are greenhouse gases, which let visible light in but absorb much of the outgoing infrared ("heat") rays. Their presence was sufficient for the planet to avoid a frozen fate. Oxygen made up only a tiny fraction of the atmosphere's present-day concentration.

CHAPTER 2
The Beginnings of Life

Some of Earth's oldest rocks (up to about 3.8 billion years old) show signs of organic compounds—carbon-containing molecules likely produced by living organisms. More definite evidence appears in rocks about 3.5 billion years old. Microscopic casts of what some scientists believe to be ancient bacteria that resembled cyanobacteria (also called blue-green algae) have been found from then. Also, certain layered rock formations dating to about that same time are thought to be stromatolites, which are formed by the growth of matlike colonies of microorganisms, especially cyanobacteria. These layered columns are still being formed by living organisms today, such as in a few spots on the western coast of Australia.

The First Organisms

The first organisms may have been prokaryotes—single-celled organisms with no

cell nucleus. Some of them started carrying out photosynthesis, which uses sunlight as an energy source to take carbon (needed to build the organisms' bodies) from carbon dioxide in the air, releasing oxygen in the process. These bacteria are thought to have been quite similar to the cyanobacteria that are still abundant today. It is likely that cyanobacteria were not the only type, and perhaps not the first type, of organism during this period. Bacteria called chemoautotrophs likely existed in the depths of the sea and even in rock. Some early organisms may have been archaeans, rather than true bacteria. Archaeans are a group of microorganisms that can live in extreme environments, such as those with particularly hot or salty conditions.

For hundreds of millions of years, the oxygen released by photosynthesizing organisms quickly reacted with materials in the environment. Oxygen therefore could not accumulate in the air to any great extent. Much of this oxygen likely combined with iron, essentially producing rust. The eon (long time period) just described—from about 4 billion to 2.5 billion years ago—is called the Archean (not to be confused with the organisms called archaeans).

The Oxygen Revolution

Most scientists agree that the Archean atmosphere contained very little oxygen, probably less than 1 percent of present-day

Photosynthesis

Without the process of photosynthesis, Earth's fundamental food supply would not replenish, and the planet would completely lack oxygen. During photosynthesis green plants harness sunlight and transform it into chemical energy. This energy is used to convert carbon dioxide, water, and minerals from the environment into sugars and oxygen—the basis of both plant and animal life.

Although photosynthesis is performed mostly by green plants, some other organisms also use it to make their own food. Among them are certain types of bacteria and other prokaryotes. Cyanobacteria, or blue-green algae, were probably the first oxygen-producing cells. These and other photosynthetic microorganisms are believed to have greatly increased the oxygen content of the atmosphere, making possible the development of aerobic (oxygen-using) organisms. Some bacteria do not produce oxygen during photosynthesis. For example, sulfur bacteria produce sulfur instead of oxygen.

levels. That changed during the first part of the next eon, the Proterozoic (about 2.5 billion to 542 million years ago). Much of the material that could combine with oxygen (that is, to be oxidized) had already done so. From about 2.5 to 1.9 billion years ago, vast deposits called banded iron formations were laid down on the ocean bottom. The deposits consist of alternating, extremely thin layers of iron-rich minerals and silica minerals such as chert. The process by which they formed is not completely understood. It appears to have occurred in response to increasing, and perhaps fluctuating, amounts of free oxygen in the atmosphere and oceans. These formations are the source of most of the iron ore used today, so people are reaping the harvest of an event that occurred when Earth was only half its present age.

By 1.5 billion years ago, oxygen levels had reached perhaps 10 percent of current levels. One effect of this is that "red beds" began to form. These are areas where iron in the soil has been oxidized and appears rusty. This process happens mainly in dry, hot climates, such as the present-day Australian outback, often called the "red center."

A more important consequence of increased oxygen levels was a dramatic change

A banded iron formation (BIF) rock recovered from the Temagami greenstone belt in Ontario, Canada, dates to 2.7 billion years ago. Dark layers of iron oxide alternate with red chert. **Prof. Dr. Michael Bau/ Jacobs University Bremen**

in Earth's life. Oxygen is poisonous to many microorganisms (such as the tetanus bacterium, which thrives in closed wounds with little oxygen). Much of this life perished, but some of it found refuge deep in the sea or underground. A more complex type of single-celled living thing arose at about this time—eukaryotes. These organisms have a

cell nucleus and many other structures not present in prokaryotes. More complex, multicellular eukaryotes also evolved later. In fact, all animals, plants, fungi, and protists are eukaryotes.

Eukaryotes require something that prokaryotes do not—oxygen at levels at least 1 percent of the present level. Once sufficient oxygen was present, eukaryotic cells flourished. For most of the remainder of the Proterozoic, all life on Earth consisted of single-celled organisms, including both prokaryotes and eukaryotes.

MULTICELLULAR LIFE

Near the end of the Proterozoic eon, the climate changed dramatically. Since the Hadean eon, conditions had apparently been much like today's. About 750 million years ago, however, temperatures drastically plunged. Rocks from that time show evidence of the action of glaciers, and some rocks appear to have formed near the ancient Equator. Many scientists believe that Earth froze over, even at the Equator, for millions of years—a state called "snowball Earth." This seems to have occurred at least twice, probably about 710 million years ago and 640 million years ago.

(Some evidence also points to widespread glaciation much earlier, about 2.2 billion years ago). Other scientists do not believe the glaciation was quite this extensive, suggesting instead that open water and some bare land were present in the tropics. In either case, the climate was probably colder than at any time since.

How might such a frigid spell have occurred? By this time, the supercontinent Rodinia had begun to break apart, with many fragments likely in tropical regions. Carbon dioxide, dissolved in rain falling on the continent and also in water in waves smashing against the shores, weathered the rocks. This washed calcium ions into the sea, where they combined with carbon dioxide to make limestone. Photosynthesizing organisms in the ocean continued to take carbon dioxide from the air and to bury the carbon as they died and sank to the bottom. With less of this greenhouse gas present, and the Sun at only about 94 percent of its present brightness, temperatures began to drop. Once snow and ice began to form, they reflected more of the Sun's light away. This vicious circle is an example of "positive feedback," in which an effect itself causes more of the same effect to occur. It allowed

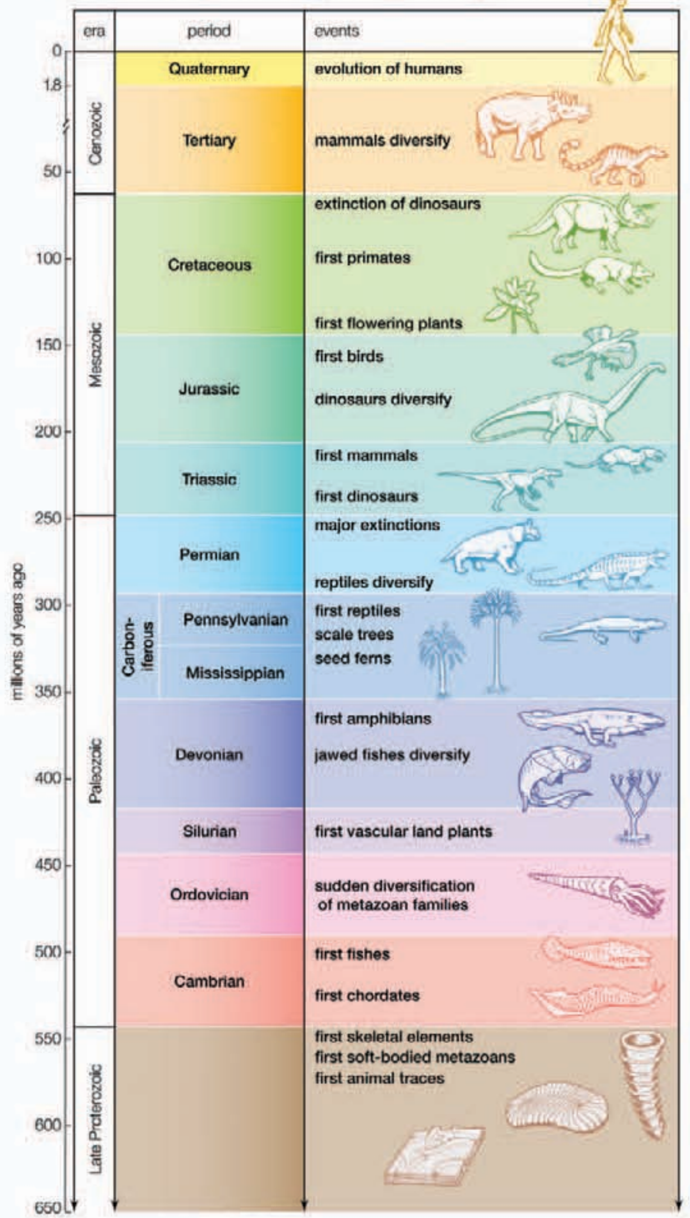
the world's average temperature to plunge to perhaps -60 °F (-50 °C).

After perhaps millions of years in this state, continuing volcanic activity continued to release carbon dioxide. However, now there was little or no rain to weather rocks, and almost all rocks were covered by ice or snow anyway. This allowed carbon dioxide levels to increase in the air again, perhaps reaching hundreds of times the present-day concentration. Temperatures became warm enough for some of the ice to start melting, exposing darker surfaces that could absorb more sunlight. A positive-feedback warming process then sent the planet into a very hot state, with Earth reaching average temperatures of perhaps 100 °F (38 °C). The freeze-over had reduced the amount of life available to remove the carbon dioxide from the air. Earth may have gone through at least two such freeze-thaw cycles in the late Proterozoic.

These stresses may have played a role in the next revolution of the biosphere—the

A geologic time scale shows major evolutionary events from 650 million years ago to the present.
Encyclopædia Britannica, Inc.

Geologic time scale, 650 million years ago to the present



appearance of multicellular life. Evolution can occur rapidly when the environment changes dramatically. Fossils from as much as 600 million years ago appear to be the imprints of soft-bodied creatures. Some of these, called the Ediacarans, appear as round, fanlike, or "quilted" impressions. Their relationship, if any, to later animals is unclear. Relatively little is known about these creatures, but as the Proterozoic ended, an explosion of new life-forms was about to take place.

CHAPTER 3
Paleozoic Era

Dramatic changes occurred on Earth around 542 million years ago, heralding the beginning of the Paleozoic (meaning "old life") era. The glaciers of the late Proterozoic melted. This, combined with changes on the seafloor, led to a rise in sea level, which flooded the coastlines of the ancient continents. Earth became warmer—somewhat warmer than today. Oxygen had recently increased to perhaps half its present-day level (though there is considerable uncertainty regarding the amount). These changes set the stage for a rapid phase of evolution called the Cambrian explosion.

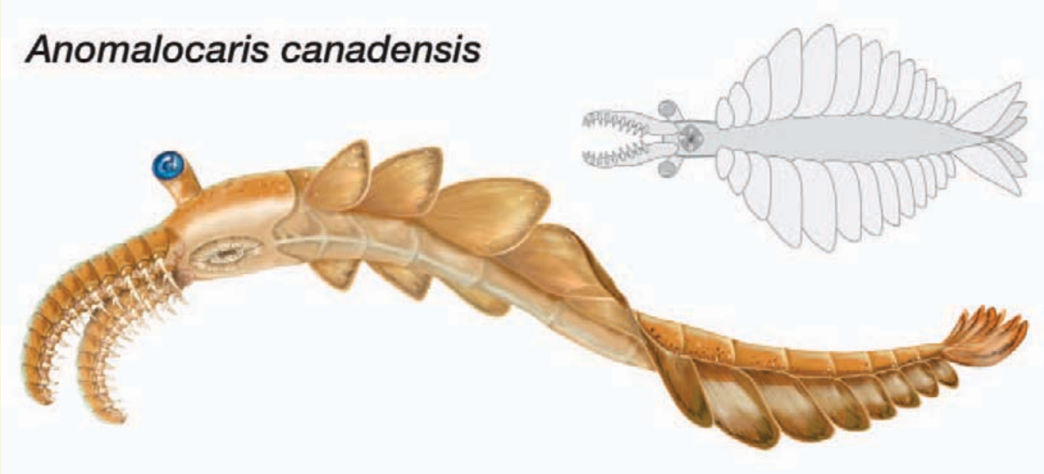
Cambrian Period

The Cambrian period lasted from about 542 million to 488 million years ago. Fossils are very scarce in older rock layers but suddenly quite abundant in the Cambrian. It was once thought that no life, or at least nothing other than single-celled organisms, preceded it. Some fossils from earlier times

have now been found, but the dramatic increase requires an explanation.

One factor is that at about this time animals developed the ability to form hard parts, such as exoskeletons or shells. These structures are much more easily preserved than the soft parts of creatures. However, it is likely that the actual numbers of animals, and certainly the number of types of animals, increased greatly. Many scientists believe that almost all the large groups called phyla in the animal kingdom appeared at this time. For example, the ancestors of arthropods (such as today's crabs, spiders, and insects), mollusks (snails, clams, squid), poriferans (sponges), and echinoderms (starfish, sea urchins) are present in Cambrian sediments. These creatures lived in the sea. The first fishes, which were jawless, also appeared. There is only limited evidence of any life on land during this time, and any land dwellers that did exist were probably single-celled organisms such as bacteria.

Though the creatures of the Cambrian were mostly related to those of today, some would look unfamiliar, even bizarre, to people today. A very common animal in the sea was the trilobite, an early arthropod.



A sketch shows **Anomalocaris canadensis.** *Members of the genus* **Anomalocaris** *were the largest marine predators of the Cambrian period.* **Encyclopædia Britannica, Inc.**

There were thousands of species of these segmented creatures, which looked something like a rib cage. They varied from the size of a coin to about 18 inches (46 centimeters) long. Many of them may have fed on algae or other small organisms, though some may have eaten larger prey. The trilobites appeared very early in the Cambrian period and lasted nearly 300 million years, almost through the entire Paleozoic era.

Trilobites apparently had at least one creature to fear—*Anomalocaris*—meaning "strange shrimp." These creatures were

evidently predators, with two curved, spiny appendages protruding from the front, a mouthlike feature on the underside, and two large eyes. They generally grew up to 2 feet (about 60 centimeters) in length. Some fossilized trilobites have been found with apparent bites taken out of them, possibly by *Anomalocaris*.

The rest of the Paleozoic era consisted of periods called the Ordovician (488 million to 444 million years ago), the Silurian (444 million to 416 million years ago), the Devonian (416 million to 359 million years ago), the Carboniferous (359 million to 299 million years ago), and the Permian (299 million to 251 million years ago). Earth, and life itself, went through many changes during this time. These periods are distinguishable by significant changes in the sediments and in the fossil records, corresponding to environmental changes and extinctions of many species.

Rodinia broke apart, with the continents becoming most widely scattered about 470 million to 450 million years ago, during the Ordovician period. Then, the increasingly compacted seafloor started to be subducted under the edges of plates carrying the continents as they turned around and began to approach each other.

FOSSILS

Fossils are the remains or traces of plants and animals that lived in prehistoric times. Most fossils are found in earth that once lay underwater. They usually formed from the hard parts—such as shells or bones—of living things. After a living thing died, it sank to the bottom of the sea. Layers of earth and the remains of other living things built up on top of it. Over time these layers turned into rock, and eventually part or all of the living thing's hard parts also turned into rock. The fossil is the shape of these hard parts in the rock.

Other kinds of fossils are imprints on soft material that later hardened into rock. For example, scientists have found dinosaur footprints in rock that formed from mud.

Another kind of fossil can form after a small insect or a piece of a plant gets trapped in resin—a sticky substance made by pine and fir trees. When the resin hardens into a rocklike material called amber, the object inside is preserved.

A fossilized marine snail of the extinct genus Lophospira *dates to the Ordovician period. The fossil was found in rocks in Canada.* Courtesy of the trustees of the British Museum (Natural History); photograph, Imitor

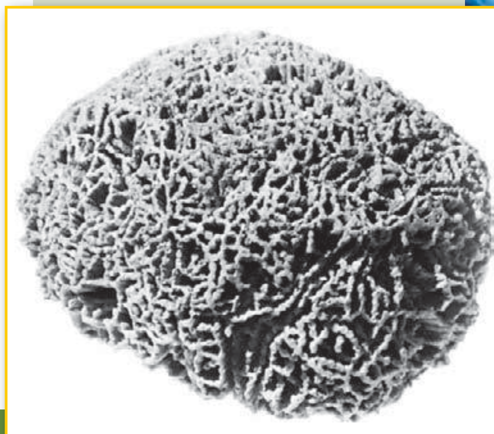
A fossilized animal from the extinct genus Echinosphaerites *dates to the Ordovician period. The animal was a spherical, stalked echinoderm related to the sea lily and starfish.* Courtesy of the trustees of the British Museum (Natural History); photograph, Imitor

Ordovician Period

During the Ordovician period the continents were generally spread apart. Most of Earth's land was in the Southern Hemisphere, and most of this was concentrated in the large continent of Gondwana. For most of the period the sea level was high and temperatures were warm. Many of the groups of marine organisms that had appeared in the Cambrian became more diverse. Arthropods, as well as primitive plant life and fungi, are thought to have begun to colonize the land. Toward the end of the Ordovician, though, a large part of Gondwana lay near the South Pole. Glaciation developed there, the sea level dropped, and the world became colder. This led to the extinction of many species.

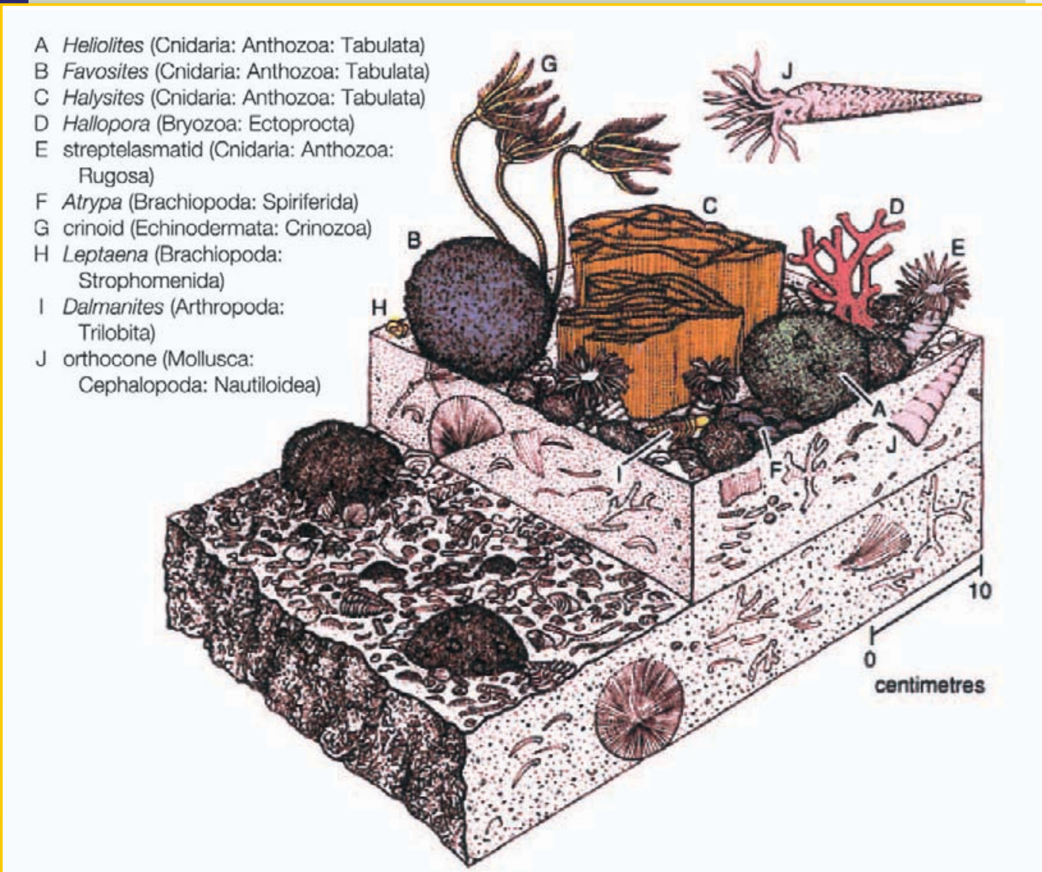
Silurian Period

During the Silurian period, the continents began to approach each other once again. Most of



***A fossilized* Halysites catenularia*, an extinct type of coral, dates to the middle of the Silurian period. It was collected from the Lockport Dolomite in western New York.* Courtesy of the Buffalo Museum of Science, Buffalo, N.Y.**

the late Ordovician ice melted, and the world became relatively warm. Large coral reefs were quite common. Jawless fish became plentiful, and some fish with jaws appeared



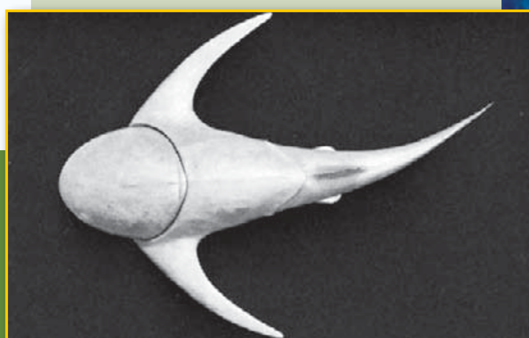
Several species of animals lived in a certain type of reef community on the seafloor during the early Silurian period. This type of reef was built by various corals and stromatoporoids, which were a type of sponge with a layered skeleton. **From E. Winson in W.S. McKerrow (ed.), *The Ecology of Fossils*, Gerald Duckworth & Company Ltd.**

late in the period. Vascular plants—that is, plants with a system for transporting water and nutrients—were living on land, though they did not have definite stems and leaves. Worms, centipedes, and spiders added to the growing biological communities on land.

DEVONIAN PERIOD

The Devonian period saw the continued approach of the continents. Plant life spread on land, and carbon dioxide levels in the air probably dropped because of the increasing photosynthesis. There is evidence of glaciers in southern Gondwana late in the period. The Devonian is sometimes called the Age of Fishes, because many new

A reconstructed head of Dinichthys terrelli, *a species of jawed, armored fish, is from the Devonian period. Fish of its genus (now extinct) were the dominant marine predators of the time. Some grew up to 30 feet (9 meters) in length.* Courtesy of the Cleveland Museum of Natural History



Arctolepis *was a small-jawed, armored fish of the early Devonian period.* Courtesy of the American Museum of Natural History, New York

kinds, including sharks, appeared. Near the end of this time, tetrapods—four-legged animals likely descended from fish—first appeared on land. The first ones were similar to amphibians and are believed to be the ancestors of modern amphibians, reptiles, birds, and mammals.

CARBONIFEROUS PERIOD

The Carboniferous period is so named because it was during this time that vast amounts of carbon were buried by plant life

A fossil preserves the skeleton of an amphibian from the extinct genus **Eryops**, *which lived during the Carboniferous and Permian periods. The massive animals of this group probably remained close to water, favoring the abundant swamps of the time.* **Courtesy of the trustees of the British Museum (Natural History); photograph, Imitor**

in forests and swamps. This same plant life liberated huge amounts of oxygen, which may have made up as much as 35 percent of the atmosphere. Forest fires must have burned with particular intensity.

Another interesting effect was that high oxygen levels are thought to have allowed some insects to become larger. Insects do not have lungs but absorb oxygen through their exoskeletons. This severely limits

A diorama shows what a forest from the late Carboniferous period would have looked like. **Courtesy of the Department Library Services, American Museum of Natural History, neg. #333983**

their maximum size. If the height, length, and width of an insect are all doubled, it will have eight times the volume and mass and will need eight times the energy. However, it will have only four times the surface area through which to absorb oxygen. Such an underpowered insect might not be able to function or even survive. With twice as much oxygen in the air, though, it would have enough energy after all. Perhaps because of this, certain huge insects, such as dragonflies with wingspans of up to 30 inches (76 centimeters), were able to thrive.

The carboniferous swamp forests featured tall, fast-growing treelike plants, such as the *Lepidodendron*, or "scale trees." Some grew to heights of more than 100 feet (30 meters). Giant horsetails and ferns were also present. When these treelike plants died and fell, they formed dense mats of logs that were slow to rot, perhaps because appropriate microbes had not yet evolved to rapidly consume the dead matter. The logs and other plant matter were gradually buried and became the coal beds from which people extract so much fuel today.

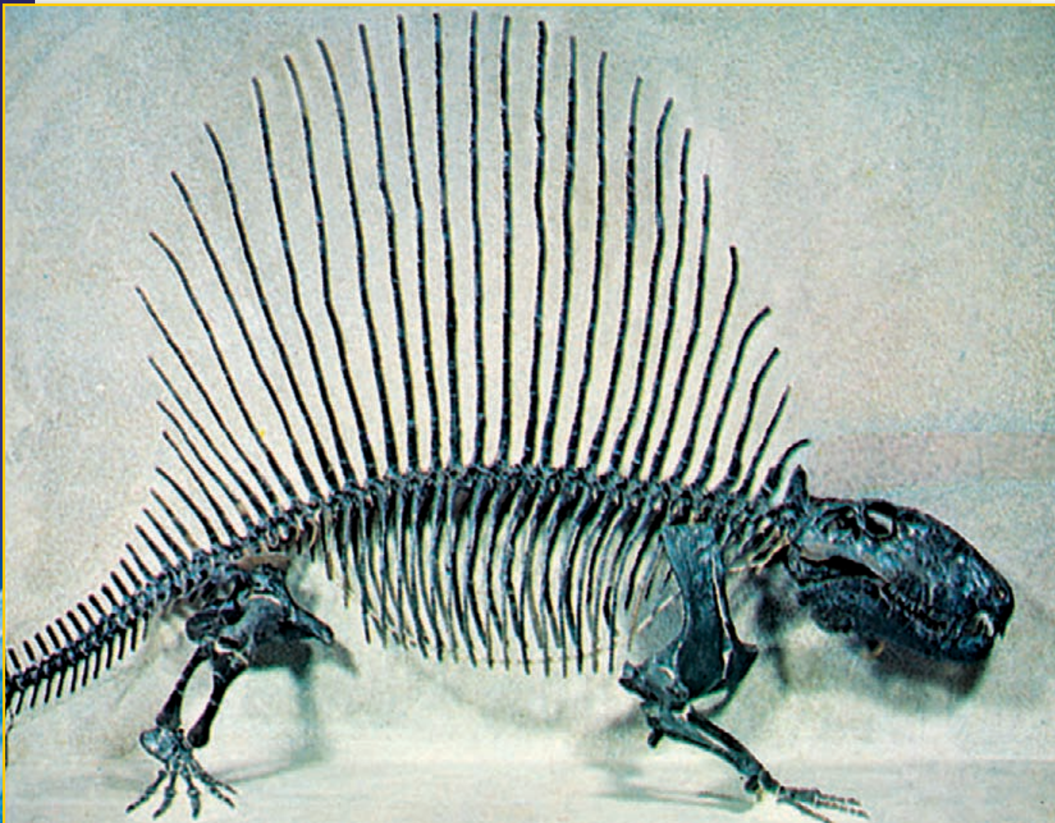
Some of the largest forest belts were in what are now eastern North America and northwestern Europe. These regions

were apparently in the tropics at the time. Southern Gondwana had reached the South Pole, and millions of years of snow had built an ice cap there. The planet as a whole was colder than it had been. The large temperature difference between the poles and the Equator produced strong trade winds, which brought moisture from the ocean well inland. The resulting heavy rains enabled the rapid growth of these forests.

PERMIAN PERIOD

As the Permian began, the continents reassembled to form Pangea. Much of the land was then very far from any water. Much of Pangea became desert, and plant life on land was reduced. The southern ice cap diminished or disappeared, and the world became warmer. The great carboniferous forests diminished and were largely replaced by ferns and early conifer trees. Broad-leaved deciduous trees called *Glossopteris* became common in the south. A drop in sea level exposed sediments containing materials such as iron, which could then take oxygen from the atmosphere.

Land animals included early reptiles as well as creatures with characteristics



A restored **Dimetrodon** *skeleton shows the long spines on the back that were likely connected by a sail-like membrane.* **Dimetrodon** *was a carnivorous animal of the Permian period. It had characteristics of both reptiles and mammals. The therapsids, from which mammals likely evolved, are thought to have descended from animals similar to* **Dimetrodon. Courtesy of the American Museum of Natural History, New York**

of both reptiles and mammals. The latter included the curious *Dimetrodon*, which had a sail-like membrane protruding from its back, and predators called gorgonopsids.

The gorgonopsids were part of the group called the therapsids, from which mammals likely evolved.

The Great Dying

Geologic periods in general are defined by fairly sharp differences in the strata, or layers, of sediment. One of the differences seen is the fossils that predominate. In other words, the periods tend to be separated by extinction events, and the major eras are separated by especially large extinction events. The Paleozoic ("old life") and Mesozoic ("middle life") eras are separated by the most dramatic extinction event known—that which separates the Permian period from the Triassic period. Roughly 95 percent of all marine species and 70 percent of all land-based species became extinct. Even species that survived probably experienced significantly decreased populations.

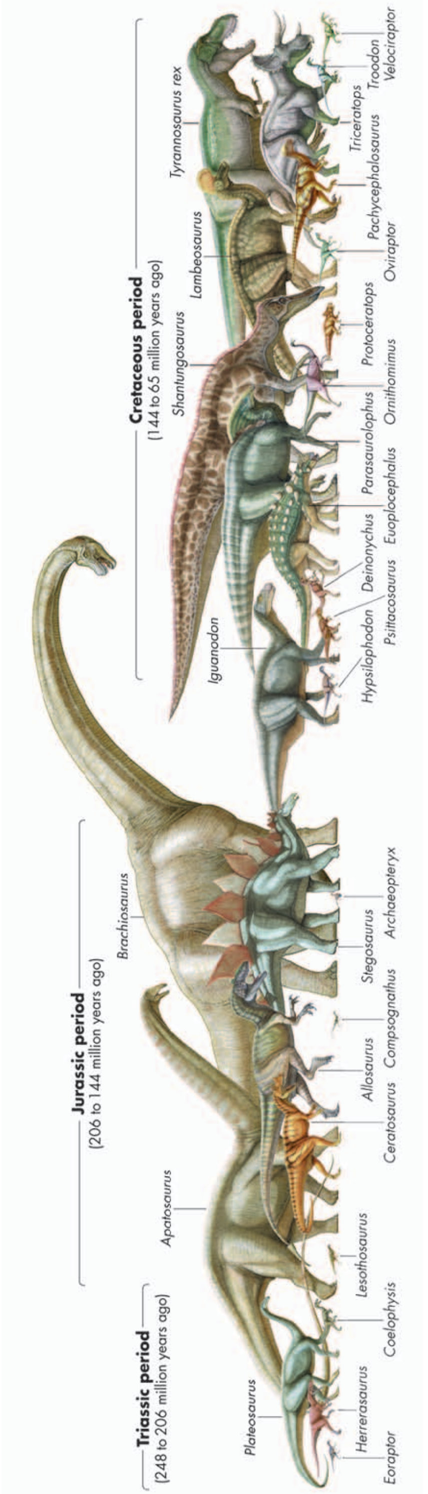
This "great dying," known as the Permian-Triassic extinction, occurred about 251 million years ago. There were actually a series of extinctions in the middle and late Permian. The final extinction event took place over a period of less than a million years and possibly as little as several thousand years. The

cause is not known with any certainty, but there have been many theories. It was quite possibly a combination of factors. A tremendous amount of volcanic activity occurred in what is now Siberia, Russia, at about that time, lasting about a million years. This released between 250,000 and 1 million cubic miles (1 million and 4 million cubic kilometers) of lava, which hardened into basalt. That would have been enough to cover the world in a layer about 6 to 25 feet (about 2 to 8 meters) deep, if the basalt had been spread out evenly. Such an event would likely cause large climate changes and acid rain and disrupt ecosystems.

Scientists also believe that oxygen was reduced at the time, to perhaps as little as half its present abundance. It has been suggested that there was a large release of methane that had been trapped underground and under the sea. Such a release of methane could have caused an intense greenhouse effect and warming and could also lower oxygen levels. Also, the assembly of Pangea may have reduced the amount of shallow seas, which were needed to sustain many marine communities.

Another possibility is that a large comet or asteroid struck Earth at that time, triggering

an environmental catastrophe. Some scientists believe that a feature found under the Antarctic ice or one found on the sea bottom off the coast of Australia could be the resulting crater. It may be that all of these suggested causes played a role or were interrelated—such as the impact triggering the volcanic activity. Even though no consensus has been reached on this, scientists agree that studying such extinctions is important, because life on Earth could be similarly threatened in the future.



CHAPTER 4

Mesozoic Era

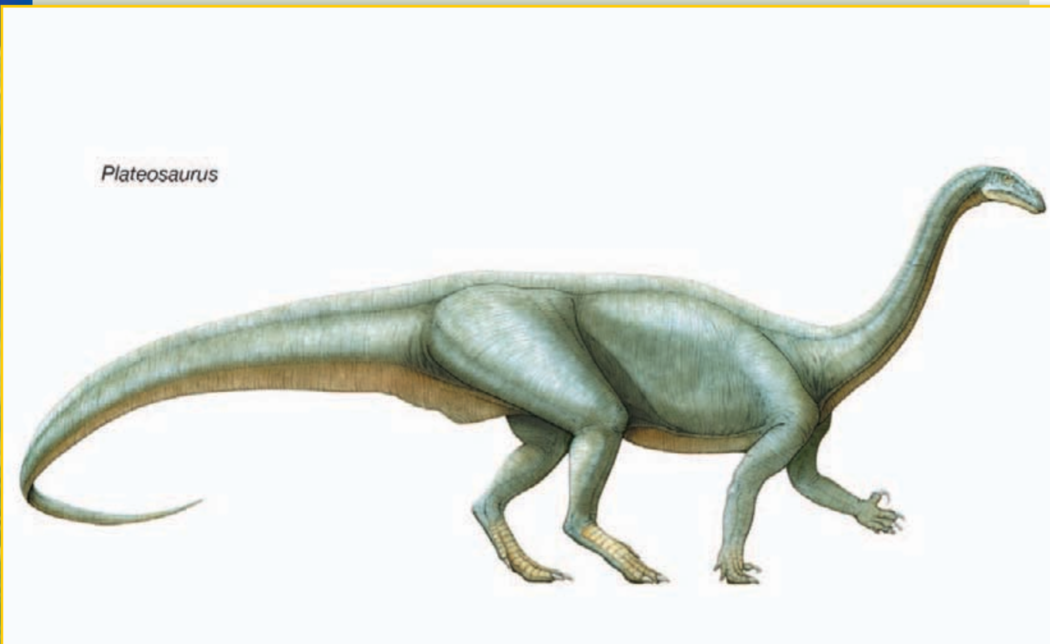
The Mesozoic ("middle life") era lasted from 251 million to about 66 million years ago. It is divided into three periods: the Triassic (251 million to 200 million years ago), the Jurassic (200 million to 146 million years ago), and the Cretaceous (146 million to 66 million years ago). This era is more familiar to most people than the Paleozoic is, because the Mesozoic was the age of the dinosaurs. Each of the periods ended with some degree of extinctions, but the most dramatic event occurred at the end of the Cretaceous. While not as extensive as the Permian-Triassic event, it nonetheless put an end to the dinosaurs and paved the way for the rise of mammals.

(Left) Dinosaurs of the Jurassic and Cretaceous periods. *Encyclopædia Britannica, Inc.*

Reptiles such as dinosaurs dominated Earth during the Mesozoic. Scientists at Dinosaur National Monument in Colorado carefully dig the fossil bones of one of these ancient creatures from the rocky face of a quarry wall. **National Park Service**

TRIASSIC PERIOD

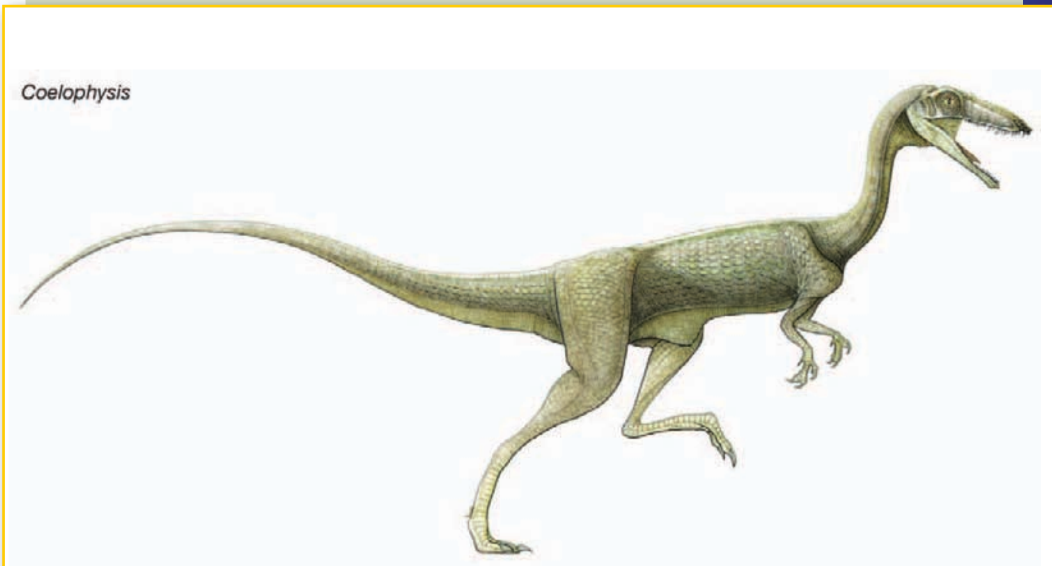
The early Triassic saw the continued existence of Pangea and a slow recovery from the preceding extinctions. The world rapidly became populated by many individuals of relatively few species, so there was little biological diversity. With Pangea straddling the Equator, much of the continent was hot and dry. Areas farther from the Equator probably had fairly harsh seasons, with hot summers



Plateosaurus ***was a dinosaur of the late Triassic period.*** **Encyclopædia Britannica, Inc.**

and rather cold winters, along with large seasonal differences in rainfall. In the late Triassic, Pangea began to break apart.

The northern and southern parts of Pangea had rather different sorts of plants and animals. In the south, forests of seed-ferns replaced the *Glossopteris* that had dominated the Permian. In the north, cycads (looking something like a cross between a fern and a palm), ginkgos, and primitive evergreen conifers were common. In the south, the animal life featured therapsids, while in the north, primitive reptiles known

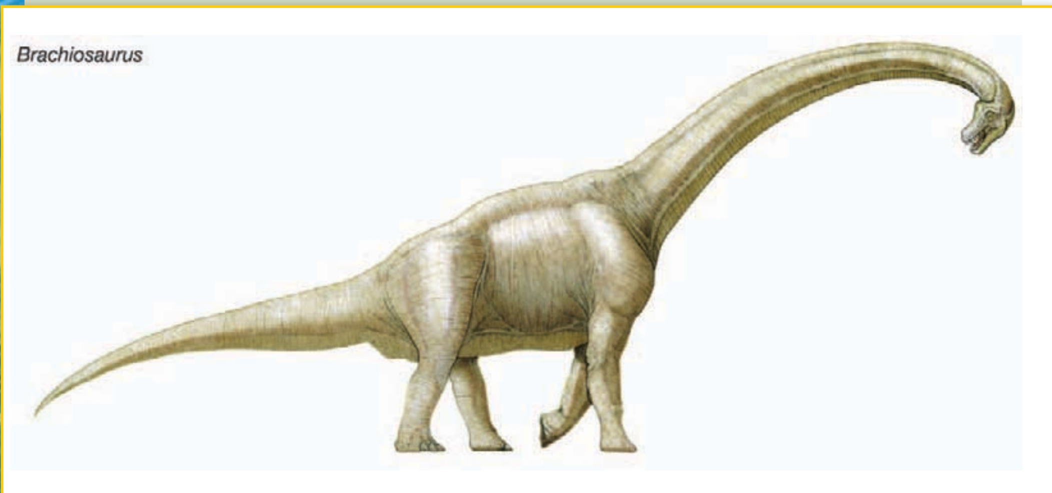


Coelophysis ***was a dinosaur of the late Triassic period.*** **Encyclopædia Britannica, Inc.**

as archosaurs were predominant. In the sea, fish were plentiful, but aquatic reptiles such as ichthyosaurs appeared as well. Late in the Triassic, early dinosaurs became common, apparently having evolved from the archosaurs. The small shrewlike creatures that were the first mammals also appeared late in the period. They may have descended from the therapsids.

JURASSIC PERIOD

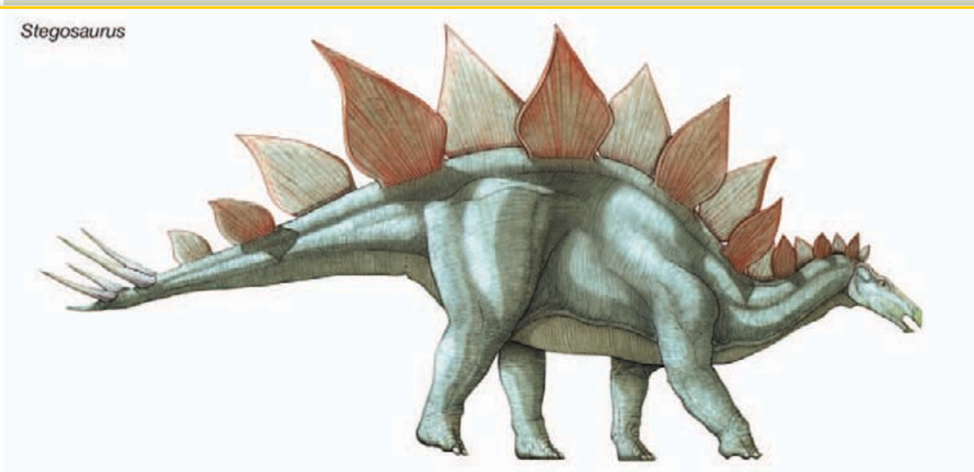
During the Jurassic period, Pangea continued to break up. The rifts between the



The enormous dinosaur **Brachiosaurus** *lived during the late Jurassic and early Cretaceous periods.* **Encyclopædia Britannica, Inc.**

splitting continents became shallow seas, and rising sea levels flooded parts of the continents. Reefs grew in the seas. The climate was generally warmer than today. Conifers and ginkgos were common plants, and cycads were abundant. Forests grew where Australia and Antarctica began to separate, eventually becoming coal deposits.

Some dinosaurs reached enormous sizes, with plant-eating sauropods such as *Brachiosaurus* growing up to 40 feet (12 meters) tall and weighing up to 80 tons. The herbivores were pursued by carnivorous theropods such as *Allosaurus*. Some herbivores,



Stegosaurus*, a massive plated dinosaur, lived during the late Jurassic period.* **Encyclopædia Britannica, Inc.**

such as *Stegosaurus*, developed self-defense features such as armored plates and bony spikes. The featherless flying and gliding reptiles called pterosaurs were common. Some of the smaller carnivores developed feathers and may also have begun to fly, evolving into the first birds. Mammals existed but were small.

CRETACEOUS PERIOD

During the Cretaceous (meaning "chalk-bearing") period, the Atlantic Ocean widened. The southern continent of Gondwana broke apart completely, and the equatorial Tethys Sea began to narrow as Africa drifted north toward Europe. India moved north toward Asia. The climate was warm, perhaps in part because of the way the continents were distributed but also likely from high levels of carbon dioxide released in the air from frequent volcanic activity. Forests, rather than ice, were to be found in the Arctic and Antarctic regions.

Thick deposits of chalk—the bodies of countless shell-producing marine organisms—were laid down in the shallow seas. Much of the deep ocean was largely devoid of life, though, as poor ocean

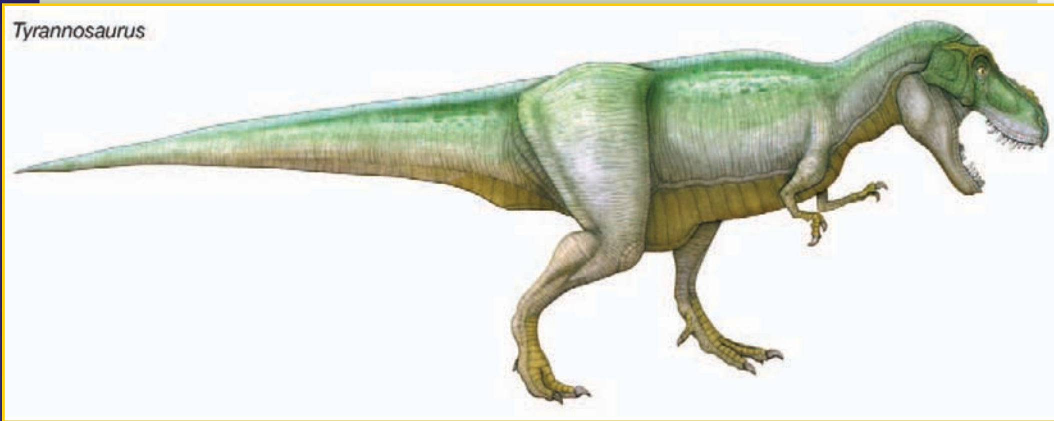
circulation deprived the depths of oxygen. Large reef systems developed, but many were apparently built by large mollusks called rudists, rather than by corals. Large reptiles, such as plesiosaurs, swam in the sea.

Flying reptiles were common but declining, with the huge *Pteranodon* and *Quetzalcoatlus* remaining until the end. Primitive birds

Chalk

In its natural state chalk is a relatively soft, white, fine-grained variety of limestone. It is composed primarily of the shells—calcium carbonate ($CaCO_3$)—of microscopic one-celled organisms known as foraminiferans. When the foraminiferans die, their shells sink to the sea floor, mix with lime muds, and eventually harden into chalk deposits.

The biggest chalk deposits were formed during the Cretaceous period that began about 146 million years ago and lasted for about 80 million years. The famous white cliffs of Dover, England, are made of Cretaceous chalk that has been thrust upward by geological forces. The same formation stretches under the English Channel into France. Extensive deposits also occur in the U.S. states of Arkansas, Louisiana, Texas, and Wyoming.

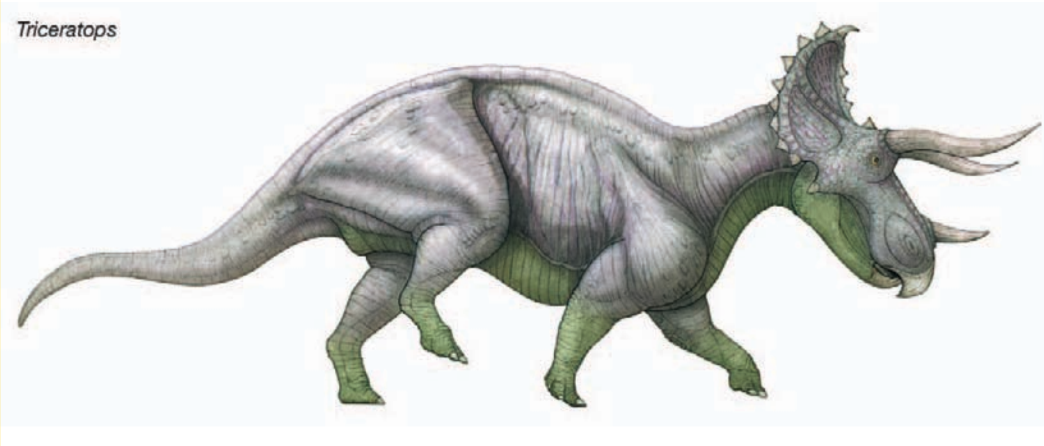


***The large, powerful predator* Tyrannosaurus *lived during the Cretaceous period.* Encyclopædia Britannica, Inc.**

continued to evolve from the theropod dinosaurs. Other theropods included the fearsome *Tyrannosaurus rex*. Plant eaters such as *Ankylosaurus* and *Triceratops* evolved defensive plates and spikes.

A major revolution in plants occurred during the Cretaceous—angiosperms, or flowering plants, first appeared. The landscape, formerly probably all shades of green, may have begun to take on other hues as these plants developed attractive flowers to lure insects, which could carry pollen. In response, insects themselves rapidly diversified into new forms.

Fairly modern reptiles, such as crocodiles and turtles, are seen in Cretaceous strata.



The large plant eater **Triceratops**, *which lived during the late Cretaceous period, was one of the last dinosaurs to evolve.* **Encyclopædia Britannica, Inc.**

Mammals developed into all three of their current groups: placentals, marsupials, and monotremes. The dinosaurs still dominated, though, and mammals remained quite small, with many burrowing into the ground.

THE END OF AN ERA

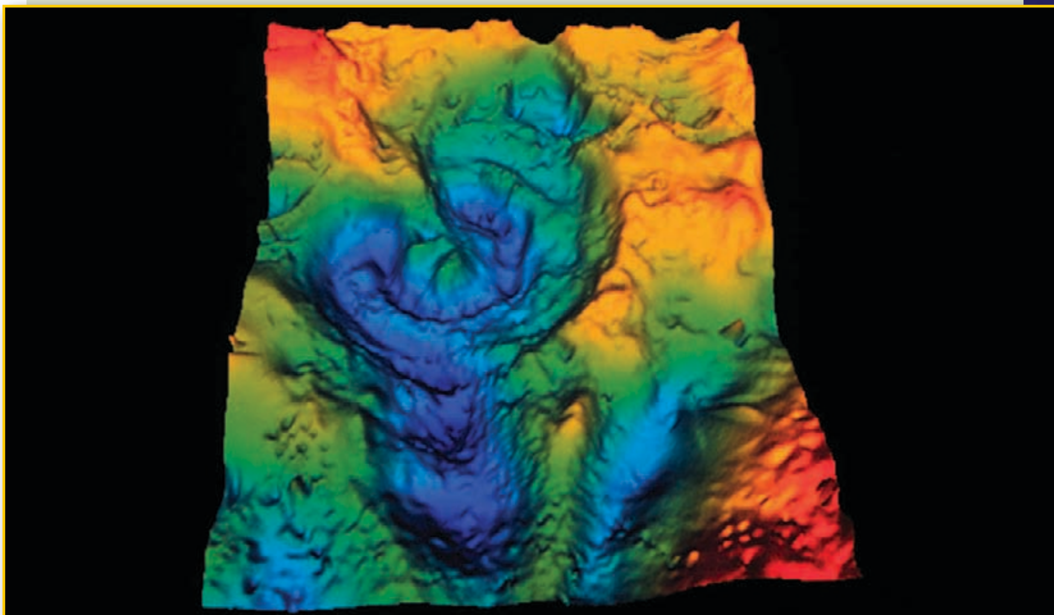
The Cretaceous ended rather suddenly 65–66 million years ago with a major extinction event that put an end to the dinosaurs (except for their apparent descendants—the birds). The rudist reefs also disappeared from the shallow seas. While not quite as severe as

the Permian-Triassic event, this extinction is one of the worst known, as nearly 80 percent of all species were destroyed.

As with the end of the Permian, the causes of this environmental catastrophe are debated. A huge volcanic outpouring in what is now India formed the Deccan Traps. This may have produced climate change and acid rain. For this extinction, though, many scientists believe there is a "smoking gun" to support the theory that the impact of an extraterrestrial body, probably an asteroid, played a role. Geologist Walter Alvarez discovered an excess concentration of the element iridium in the sediment layer deposited at the boundary between the Cretaceous and Tertiary periods, known as the K-T boundary. In about 1980 he and his father, physicist Luis Alvarez, proposed an explanation. They said that, because iridium is common in meteorites, the layer could be explained as debris from the impact of a large body, perhaps 6 miles (10 kilometers) across. The devastation produced by such an impact could have easily caused mass extinctions.

By the mid-1990s other researchers had accumulated strong evidence that a major

impact occurred about 65 million years ago in shallow seas at what is now the northern coast of Mexico's Yucatán Peninsula. Surveys of gravitational and magnetic fields in the region show a huge circular feature, now known as the Chicxulub crater, roughly 100



An image of the Chicxulub crater, on the northern coast of the Yucatán Peninsula in Mexico, was generated on a computer from gravity and magnetic-field data. The buried structure, which measures at least 112 miles (180 kilometers) across, is thought to be the scar remaining from the impact some 65 million years ago of an asteroid or comet measuring perhaps 6 miles (10 kilometers) in diameter. The Yucatán coastline bisects the crater through its center. **V.L. Sharpton, University of Alaska, Fairbanks; NASA**

miles (160 kilometers) in diameter. Cores drilled there by an oil company years before had revealed unusual, glassy rock at a depth of about 4,200 feet (1,300 meters). In addition, the types of rocks called breccias and tektites had been found at numerous sites around the Caribbean and North America. The breccias consisted of a mixture of fragments of different rock types fused together by heating. Tektites are believed to be material ejected from impact sites that melted and then resolidified. These samples were determined by radioactive dating to have formed at the time of the supposed impact.

The environmental consequences must have been severe. The energy of the impact is estimated to have been about 100 million megatons—the equivalent of 2 million of the most powerful nuclear bombs ever detonated. Huge tsunamis, earthquakes, and intense heat would have been almost immediate effects. Within half an hour, material ejected from the site would have reentered the atmosphere over a large fraction of the globe. The shock-heating of the air would have set off huge forest fires. Longer-term effects would have included an almost complete cutoff of sunlight reaching the ground over much

of the world for months. Chemicals produced by the event could have poisoned the air and oceans. Carbon dioxide released by the vaporization of seafloor sediment could have caused a large greenhouse effect for hundreds of years afterward.

In spite of this, there is still debate regarding the main causes of the extinction. The question also remains as to why some species survived. It is likely, though, that the impact played a role. In any case, asteroid or comet impacts can and do occur over geologic time and are a threat to life on Earth.

CHAPTER 5
Cenozoic Era

The Cenozoic ("recent life") era began about 66 million years ago and continues today. It has traditionally been divided into two rather unequal periods: the Tertiary and the Quaternary. Now, however, the periods are usually defined as the Paleogene (66 million to 23 million years ago) and the Neogene (23 million years ago until the present). The periods are divided into several epochs, with the current epoch being the Holocene (11,800 years ago to the present). The Cenozoic is often called the Age of Mammals, because mammals quickly replaced reptiles as the most prominent land animals.

Plate Tectonics

During the Cenozoic, plate tectonics brought the continents to their modern positions. India rammed into Asia, producing the Himalaya Mountains. South America—once part of Gondwana—made contact with North America for the first time since Pangea broke apart, just in the last few million years.

The Himalaya Mountains were created when plate tectonics thrust India into Asia. **Kazuhiro Nogi/AFP/Getty Images**

CLIMATE CHANGES

The climate started out very warm, with global temperatures peaking at an average of about 77 to 86 °F (25 to 30 °C), compared to the present 59 °F (15 °C). At that time, tropical conditions extended at least 45 degrees from the Equator, and even the Arctic Ocean may have had temperatures as high as 68 °F

(20 °C). Gradual cooling occurred after that, with ice eventually forming on Antarctica and Greenland.

In just the last million years or so, Earth's climate entered a new and dramatic phase. Severe ice ages have occurred roughly every 100,000 years. These ice ages have been interrupted by relatively mild intervals called interglacials lasting roughly 20,000 years. The last major cold spell peaked about 18,000 years ago, with ice sheets over a mile thick covering much of northwestern Europe and North America (as far south as Ohio). Global temperatures averaged some 9 to 14 °F (5 to 8 °C) colder than at present, with high northern latitudes much more strongly affected.

The ice began to melt rapidly about 14,000 years ago, and the present time is in the Holocene interglacial. For perspective, Earth is now considerably warmer than it has been for most of the last 100,000 years but still significantly cooler than the average of the last 250 million years.

Animals and Plants

Early in the Cenozoic, mammals and birds quickly filled many ecological niches previously occupied by dinosaurs and other reptiles.

Ice Age

An ice age is a geologic period during which thick ice sheets, or glaciers, cover vast areas of land. An ice age may last several million years and drastically reshape surface features of entire continents. A number of major ice ages have occurred throughout Earth's history. The earliest known took place more than 570 million years ago. The most recent ice age ended more than 10,000 years ago.

Scientists are not sure what caused the ice ages. Some have suggested that they resulted from variations in Earth's orbit around the Sun. These variations would have caused parts of the planet to receive less heat from the Sun at certain times. But no variation has ever been found that fits both the theories of astronomy and the record of what has happened on Earth. Other scientists have guessed that blankets of dust or carbon dioxide got into the air and cut off part of the Sun's heat.

Whatever its cause, the latest ice age left lasting marks on the land. The creeping ice carried gravel, sand, soil, clay, and even boulders, which were left behind in ridges, piles, and other formations when the ice melted. The melting ice also formed many lakes and caused sea levels to rise. As the land near the sea flooded, coastlines moved inland. Finally, the tremendous weight of the ice sheets caused Earth's crust to sink in some places—from 300

A polar map shows five great ice caps, or centers, from which the ice moved outward during the last ice age and to which it later retreated.

to 800 feet (90 to 240 meters) in areas like New England. Here the land has not yet risen to its former level, and many ancient valleys are now under the sea, forming bays and inlets. Chile and Norway present other "drowned coasts," with many fjords filling valleys that old glaciers gouged out.

Some mammals became quite large. *Indricotherium* stood up to about 15 feet (4.5 meters) high at the shoulder and weighed up to 15 tons. It ate leaves and looked something like a combination of a rhinoceros and a giraffe. Some land mammals gradually adapted to aquatic life, eventually evolving into whales and dolphins. Mammals even entered the air, as bats evolved.

The* Indricotherium *was a hornless relative of the modern rhinoceros.
De Agostini Picture Library/Getty Images

Huge carnivorous and flightless birds, some up to 10 feet (3 meters) tall, took over some of the predatory roles formerly played by the dinosaurs. Actually, because most biologists now believe that birds descended from certain types of dinosaurs, in a sense, the dinosaurs never totally died out. In fact, they diversified into the huge number of bird species alive today.

Plant life changed, too. Flowering plants eventually dominated much of the planet. These include grasses, which had appeared late in the Cretaceous but now spread and started a whole new ecosystem.

Primates became more common, eventually developing into monkeys, apes, and the ancestors of humans. Modern humans appeared probably in the last 150,000 years or so, after the cycle of ice ages and interglacials began. Human civilization, including farming and cities, did not develop until the Holocene, after the great northern ice sheets had largely receded.

CHAPTER 6
The Future of Earth

Considering all that has been learned about Earth's past and present, one can speculate in an informed way about the future of our planet. This involves exploring two basic scenarios: one in which humans have no effect or role and another in which people influence the course of events in various possible ways.

Further Plate Movements

Plate tectonics should continue at least through the reassembly and breakup of one more supercontinent. However, the radioactive isotopes that help power convection currents in the mantle are decaying all the time. Eventually, the continents will assume their final positions, and volcanoes and earthquakes will largely cease.

Changes in Life-Forms

Assuming no human (or other intelligent creature's) intervention, some forms of life

might continue for a billion years or more. The recent series of ice ages and interglacials might continue for millions of years. Eventually, however, changing continental positions, plus a slowly brightening Sun, would bring warm, ice-free climates like those of the Mesozoic. Plants and animals would develop into new forms, but some familiar types would probably survive.

There will likely be asteroid and comet impacts from time to time. A few could trigger significant extinctions and alter the course of life's development. However, if the past is any clue, some species would almost certainly survive to populate a new and somewhat different world.

Within a few hundred million years, Earth should become very warm, perhaps with rainforests even near the poles. However, some models predict that weathering rates of silicate rocks will increase, thus reducing atmospheric carbon dioxide levels enough to threaten plant life. By a

If conditions become too hot, only one-celled organisms such as prokaryotes may survive. **Heather Davies/Science Photo Library/Getty Images**

billion years out, conditions would become so hot that multicellular life-forms would succumb, and the oceans would begin to evaporate at an ever higher rate. Only single-celled eukaryotes and prokaryotes might find conditions tolerable. Later, even the eukaryotes would perish, leaving only prokaryotes or other hardy single-celled organisms. In other words, basic types of life-forms would become extinct in approximately the reverse order in which they appeared.

The Sun as Red Giant

By perhaps 1.2 billion years from now, the oceans may have completely evaporated. Even the resulting water vapor will eventually be lost, as ultraviolet radiation from the Sun breaks off water's hydrogen atoms, which will then escape into space. By 7 billion years from now, the Sun will be swelling toward its red giant stage, with its outer layers eventually reaching Earth's orbit. As the Sun loses mass into space, Earth will likely recede somewhat from it. In any case, however, the planet will become a ball of magma, glowing at thousands of degrees. Interestingly, the moons of Jupiter

The moons of Jupiter may melt as the Sun swells into its red giant phase. NASA

and Saturn (including Titan) should melt and offer at least the chance of having biospheres of their own, though not for as long as Earth had.

If Earth survives the Sun's red giant phase, it will then become a cold, barren rock when the Sun's nuclear reactions cease and the Sun shrinks to a faint white dwarf star. Earth would continue to orbit, as it had for over 12 billion years, but with a cold, dark future.

Conclusion

If the aforementioned comes to pass, the biosphere will have lasted about 5 billion years. About three-quarters of this time has already passed. This scenario is uncertain, though, largely because humans or other intelligent descendants could play a vital role. In the short term, the release of buried carbon from human activities threatens to warm the planet to levels unprecedented in modern civilization. Global warming could, among other things, cause extinctions of other species—possibly on a scale rivaling the extinctions separating adjacent geologic periods discussed earlier.

In the very long term, though, the biosphere would probably adjust to the new conditions. Eventually, in the distant future, our descendants would face the problem of the gradual brightening of the Sun. It may be feasible to redirect an asteroid so that it swings by Earth and Jupiter every few thousand years, giving Earth a gentle tug to increase its orbital radius. Another option

would be to place a large disk between Earth and the Sun to shade Earth and keep it cooler. If our descendants were actually to execute such plans, the lifetime of the biosphere might be extended by billions of years. In that case, life would have indeed helped determine its own fate.

accretion An increase by external addition or accumulation.

cyanobacteria Any of a large group of prokaryotic, mostly photosynthetic organisms; also called blue-green algae.

deciduous Shedding leaves at a certain time of the year.

erosion Gradual wearing away of rocks and soil by natural means.

eukaryote Any organism composed of one or more cells, each of which contains a clearly defined nucleus enclosed by a membrane, along with organelles (small, self-contained cellular parts that perform specific functions).

fjord Long, narrow arm of the sea, often extending well inland, that results from seawater flooding a glaciated valley.

isotopes Atoms of the same element that vary in weight because of differing numbers of neutrons.

monotreme An egg-laying mammals of the order Monotremata; living examples are the platypus and the echidnas.

nebula Any of various tenuous clouds of gas and dust in interstellar space (plural nebulae).

photosynthesis Process by which green plants and certain other organisms transform light into chemical energy.

plate tectonics The modern theory of the motions of Earth's outer layers.

prokaryote Any single-celled organism that lacks a distinct nucleus.

radioactivity Property exhibited by certain types of matter of emitting radiation spontaneously.

silicate minerals The most widespread and numerous minerals, which consist of silicon and oxygen combined with potassium, sodium, magnesium, aluminum, and many other elements.

solar nebula Huge cloud of gas and dust from which, in the nebular hypothesis of the origin of the solar system, the Sun and planets formed by condensation.

stromatolite Layered deposit, mainly of limestone, formed by the growth of cyanobacteria (blue-green algae).

subduct To descend beneath.

supercontinent A hypothetical former large continent from which other continents broke off and drifted away.

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3300 Penrose Place
Boulder, CO 80301-1806
(303) 357-1000
Web site: http://www.geosociety.org
The Geological Society of America provides information and resources that enable Earth scientists at all levels of expertise to study the building blocks of planet Earth and share their scientific findings.

National Aeronautics and Space Administration (NASA)
The Space Place

New Millennium Program Education and Public Outreach
Jet Propulsion Laboratory
Mail Stop 606-100
4800 Oak Grove Drive
Pasadena, CA 91109
Web site: http://spaceplace.jpl.nasa.gov/en/kids/index.shtml
NASA's Space Place is a joint effort by the National Aeronautics and Space Administration, the Jet Propulsion Laboratory, the California Institute of Technology, and the International Technology and Engineering Education Association. It provides space- and technology-related games, projects, animations, and facts for students.

National Museum of Natural History
Smithsonian Institution
P.O. Box 37012
Washington, DC 20013-7012
Web site: http://www.mnh.si.edu
The National Museum of Natural History is a part of the Smithsonian Institution, a world-renowned, state-of-the-art research center and museum. Students can visit the site or the museum to investigate the history of Earth, from the first

mammals to the stones and rocks that make up the planet itself.

Royal Astronomical Society of Canada
203 - 4920 Dundas Street W
Toronto, ON M9A 1B7
Canada
(416) 924-7973
Web site: http://www.rasc.ca
The Royal Astronomical Society of Canada is Canada's foremost astronomy organization. It unites amateurs, educators and professionals, and offers local programs and services throughout Canada.

WEB SITES

Due to the changing nature of Internet links, Rosen Educational Services has developed an online list of Web sites related to the subject of this book. This site is updated regularly. Please use this link to access the list:

http://www.rosenlinks.com/ies/hist

Bjornerud, Marcia. *Reading the Rocks: The Autobiography of the Earth* (Westview, 2005).

Blashfield, J.F., and Jacobs, R.P. *When Life Took Root on Land: The Late Paleozoic Era* (Heinemann, 2006).

Erwin, Douglas, and Valentine, James. *The Cambrian Explosion and the Construction of Animal Biodiversity* (Roberts, 2010).

Kelly, Erica, and Kissel, Richard. *Evolving Planet: Four Billion Years of Life on Earth* (Abrams, 2008).

Knoll, A.H. *Life on a Young Planet: The First Three Billion Years of Evolution on Earth* (Princeton Univ. Press, 2005).

Levin, H.L. *The Earth Through Time*, 8th ed. (Wiley, 2006).

Margulis, Lynn, and Dolan, M.F. *Early Life: Evolution on the Precambrian Earth* (Jones and Bartlett, 2002).

Morris, Neil. *Prehistory* (Zak, 2009).

Nield, Ted. *Supercontinent: Ten Billion Years in the Life of Our Planet* (Harvard Univ. Press, 2007).

Prothero, D.R., and Dott, R.H., Jr. *Evolution of the Earth*, 8th ed. (McGraw, 2010).

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